Measurement of same-sign WW diboson production at 13 TeV with the ATLAS detector

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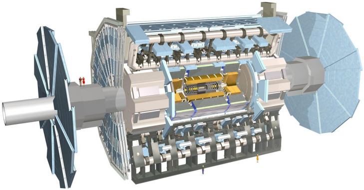
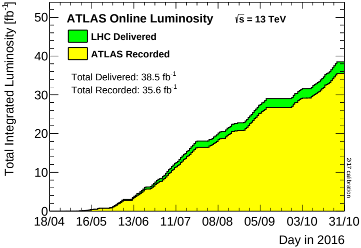
- ATLAS is one of the Large Hadron Collider's (LHC) two general-purpose detectors
- After successful data-taking campaigns at $\sqrt{s} = 7$ and 8 TeV, the energy was increased to $\sqrt{s} = 13$ TeV in 2015
    - 3.9 fb^{-1} collected in 2015
    - 35.6 fb^{-1} collected in 2016
    - 36.1 fb^{-1} combined available for physics



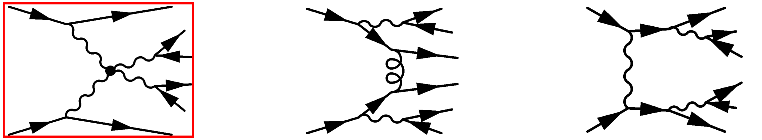
(a) The ATLAS detector (CERN).



(b) Total integrated luminosity in 2016 (AtlasPublic)

Introduction

- $W^{\pm}W^{\pm}$ events can be produced in a variety of ways:
  - Vector boson scattering (VBS)
  - Electroweak (EWK) and QCD interactions
- Events produced via EWK VBS interactions are particularly interesting
  - Sensitivity to EWK symmetry breaking
  - Sensitivity to anomalous quartic gauge couplings



(a) EWK VBS (b) QCD VBS (c) Non-VBS EWK

A selection of different production methods for a $W^{\pm}W^{\pm}$ event.

Why Same Sign?

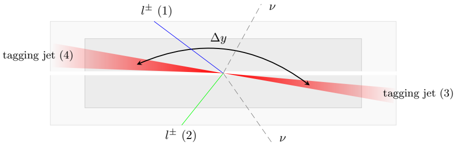
- Much cleaner backgrounds
  - Especially diboson, Z+jets, and ttbar
- Excellent ratio of EWK to QCD production compared to other VBS/VBF analyses

Final state	Process	VV-EWK	VV-QCD
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (SS)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (OS)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb

Cross sections of EWK and QCD production for several different final states relevant to VBS at $\sqrt{s} = 8$ TeV. Cross sections from leading-order Sherpa Monte Carlo with generator-level cuts applied.

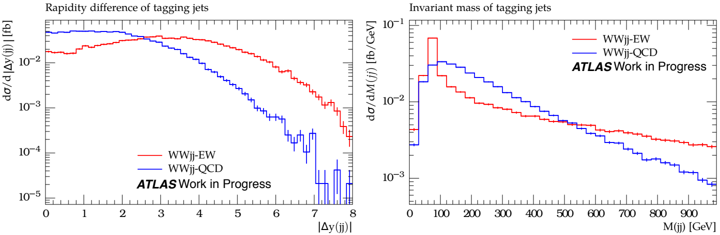
Identifying EWK VBS events

- VBS events tend to have two high-energy forward jets with large separation



Topology of a VBS event.

- Di-jet separation ($|\Delta y(jj)|$) and di-jet mass ($M(jj)$) discriminate between QCD and EWK events



Generator level comparisons of EWK and QCD production (normalized to area).

Interference between EWK and QCD

- Estimate size of interference term using $pp \to W^{\pm}W^{\pm}jj$ events generated by MadGraph at $\sqrt{s} = 13$ TeV
- Subtract cross sections of three different samples:
  - All available diagrams
  - EWK production diagrams
  - QCD production diagrams
- Cross check using interference term calculated directly by MadGraph

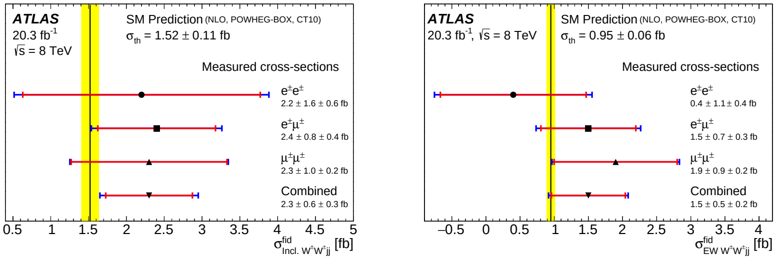
Sample	xsec (pb)
All diagrams	0.3219 ± 0.0008
QCD	0.1148 ± 0.0003
EWK	0.1849 ± 0.0004
All–QCD–EWK	0.0222 ± 0.0009
INT (MadGraph)	0.0238 ± 0.0002

EWK/QCD interference estimated using MadGraph v2.4.0 in the VBS fiducial region.

The interference is approximately 7% of the total cross section. Errors are statistical only.

Analysis Goal

- Evidence of $W^{\pm}W^{\pm}$ production seen in 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV ATLAS data
  - Expected $\sigma_{\text{fid}} = 0.95 \pm 0.06$ fb in VBS signal region
- Measure cross section using 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV data
  - Monte Carlo study predicts $\sigma_{\text{fid}} = 2.60 \pm .03$ fb in VBS signal region
- Analysis is still ongoing; signal region is currently blinded



(a) Inclusive signal region

(b) VBS region

Measured cross sections for $W^{\pm}W^{\pm} \to l^{\pm}l^{\pm}\nu\nu jj$ at $\sqrt{s} = 8$ TeV compared to Standard Model predictions (arXiv:1611.02428).

Signal Definition

- Focusing on W-bosons decaying to $e + \nu_e / \mu + \nu_\mu$
- Separated into 4 channels: ee, $e\mu$, μe, and $\mu\mu$

$W^\pm W^\pm$ Signal Region	
2 high-quality leptons with $p_\mathrm{T} > 27$ GeV	
Reject events with additional, looser leptons	diboson
Require same-charge on signal leptons	
≥ 2 anti-kt jets with $p_\mathrm{T} > 25(30)$ GeV – central(forward)	
Veto ee events within 15 GeV of Z-boson mass	Drell-Yan
Missing transverse energy $E_\mathrm{T}^\mathrm{miss} > 30$ GeV	neutrinos
Reject events with a tagged b-jet	top
Require di-jet invariant mass $M(jj) > 500$ GeV	VBS/EWK
Require di-jet rapidity $\lvert\Delta y(jj)\rvert > 2.4$	

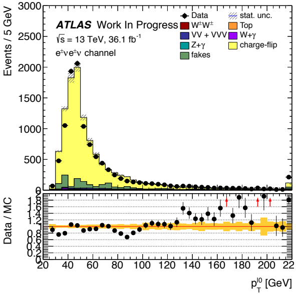
Definition of $W^\pm W^\pm$ signal events.

Backgrounds

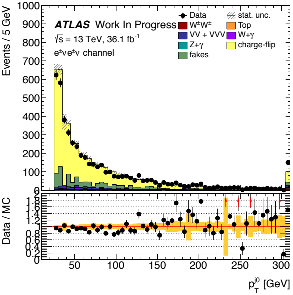
- Many other processes can mimic our $W^{\pm}W^{\pm}$ signal
  - Prompt lepton: WZ, ZZ, ttbar+V, VVV
  - Charge mis-identification (a.k.a. "charge flip"): $W^{\pm}W^{\mp}$, Z/γ^{*}, ttbar
  - Non-prompt leptons (a.k.a. "fakes"): W+jets, ttbar, single top
- Use several different methods of measuring the backgrounds
  - Estimations from Monte Carlo
  - Data-driven correction factors to handle charge flip
  - Data-driven fake-factor to handle non-prompt leptons

$W^{\pm}W^{\pm}$ Same-Sign Events

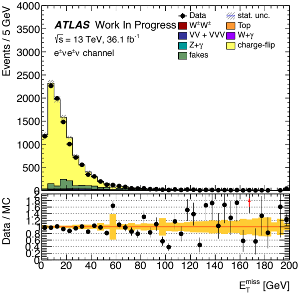
- Pre-selected same-sign events (before any additional selection)
- Initial agreement with data is good
- At this stage, $W^{\pm}W^{\pm}$ signal completely dwarfed by backgrounds
- Different channels have varying amounts of each background
  - ee channel dominated by **charge-flip** (see plots below)
  - $e\mu$, μe and $\mu\mu$ channels have large contribution from **fake leptons**



(a) Leading e p_{T}



(b) Leading jet p_{T}

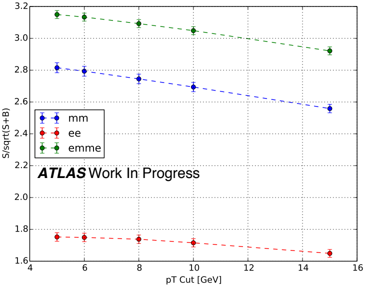


(c) Missing transverse energy

ee-channel events with pre-selected same-sign leptons. Errors are statistical only.

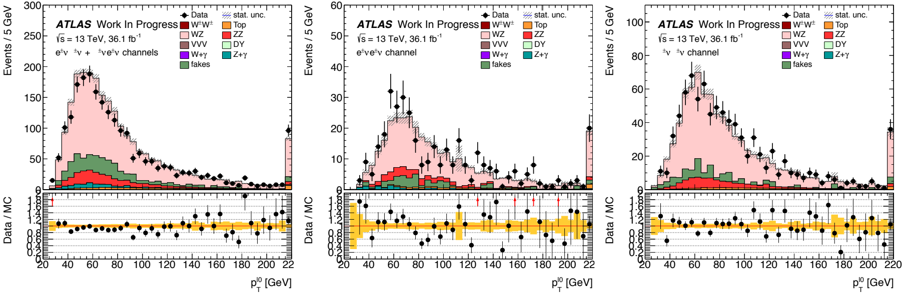
Tri-lepton Veto

- Rejecting events with an additional lepton is very effective at reducing backgrounds from other multiboson processes, especially WZ and ZZ
- Can fail to identify a third lepton
  - It fails the selection criteria
  - It falls outside the accepted region of the detector
- Define a looser set of criteria for "veto" leptons
  - Lower p_{T} cut
  - Relax identification and isolation requirements



Effect of veto lepton p_{T} on significance $\left(\frac{\text{sig}}{\sqrt{\text{sig}+\text{bkg}}}\right)$ when selecting same-sign events.

- Diboson events make up one of the major backgrounds
- Contributions are estimated from Monte Carlo
- Tri-Lepton control region tests the modeling of WZ and ZZ
  - Require exactly one veto lepton that makes a Z-mass pair with a signal lepton.

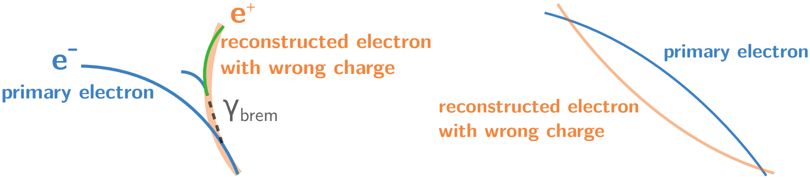


(a) $e\mu + \mu e$ channels (b) ee channel (c) $\mu\mu$ channel

Leading lepton p_{T} distributions in the Tri-Lepton control region.

Charge Mis-Identification

- Electrons have a chance to be reconstructed with the wrong charge
- Charge-flip is the dominant background for the *ee* channel
- The rate at which charge flip occurs in ATLAS has been measured and can be applied as a correction factor



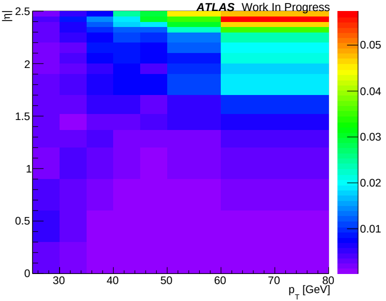
(a) Bremsstrahlung (b) Mis-reconstruction

Examples of charge-flipped electrons.

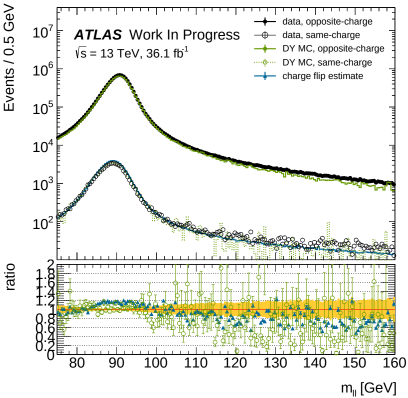
Accounting for Charge Flip

- Charge flip background is estimated using opposite-charge data corrected for the probability that an electron has the wrong charge

$$\omega = \frac{\epsilon_1(1-\epsilon_2) + (1-\epsilon_1)\epsilon_2}{(1-\epsilon_2)(1-\epsilon_1) + \epsilon_1\epsilon_2}$$



Charge flip rate $\epsilon_i(p_{\mathrm{T},i}, \eta_i)$.



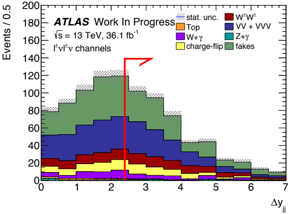
Di-lepton invariant mass in Z-boson events.

Status & Outlook

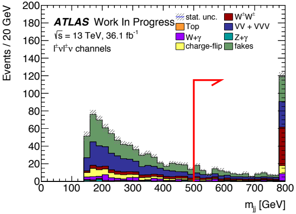
- Approximately 50 $W^{\pm}W^{\pm}$ events to 150 background events expected in the signal region (predicted from Monte Carlo)

Signal Region	
$W+\gamma/Z+\gamma$	13.5
WZ/ZZ	52.1
Top	1.0
Fakes	65.7
Charge-flip	17.3
Background	149.6
$W^{\pm}W^{\pm}$	50.4

Expected yields (all channels). Color coded to match plots.



(a) Di-jet separation



(b) Di-jet invariant mass

Di-jet quantities for all channels in the signal region.

Conclusions

- Same-sign WW events are particularly interesting to study
  - Large ratio of EWK to QCD production
  - Sensitivity to EWK symmetry breaking, anomalous couplings
- Looking to build off of $\sqrt{s} = 8$ TeV cross section measurement
  - Expect greater sensitivity due to increased $\sqrt{s}$ and luminosity
- Analysis still in progress
  - Signal region remains blinded

Backup Slides

QCD/EWK cross section generator-level cuts

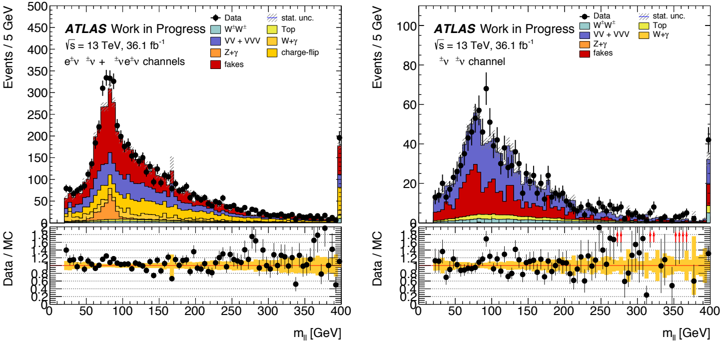
- SHERPA leading-order at $\sqrt{s} = 8$ TeV
- $p_{\mathrm{T},l} > 5$ GeV
- $M_{ll} > 4$ GeV (to suppress contributions from $\gamma*$)
- At least 2 jets with $p_{\mathrm{T},j} > 10$ GeV

QCD/EWK interference generator-level cuts

- MadGraph v2.4.0
- Generated in a (currently outdated) version of the fiducial region:
  - $p_{\mathrm{T},l} > 25$ GeV
  - $p_{\mathrm{T},j} > 30$ GeV
  - MET$>$ 40 GeV
  - $m_{ll} > 20$ GeV
  - $m_{jj} > 500$ GeV
  - $|\eta_j| < 4.5$
  - $\Delta R_{ll} > 0.3$
  - $\Delta R_{lj} > 0.3$

M_{ll} distributions in $e\mu$ and $\mu\mu$ channels

- (Using a different update of the fake-factor)



$e\mu + \mu e$- and $\mu\mu$-channel events with pre-selected same-sign leptons.